

# Displaced Dark Matter at Colliders

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Models in which the dark matter is very weakly coupled to the observable sector may explain the observed dark matter density, either as a “superWIMP” or as “asymmetric dark matter.” Both types of models predict displaced vertices at colliders, with a rich variety of possible phenomenology. We classify the cases in which the decays can naturally occur inside particle detectors at the LHC, with particular focus on the nontrivial scenarios where the decaying particle is invisible. Identification of the position and timing of these invisible displaced vertices significantly improves the prospects of reconstructing the new physics in models such as supersymmetry. In many cases, reconstruction of the visible products of the displaced decay can determine the dark matter mass, allowing the dark matter density to be predicted from collider data.

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## I. INTRODUCTION

The nature of the dark matter that accounts for about one quarter of the mass of the universe is one of the most important open questions in particle physics and cosmology. One simple possibility is that the dark matter is a massive particle  $X$  whose relic density today results from the freeze-out of the interactions  $\bar{X}X \leftrightarrow \text{SM}$ , where SM are standard model particles. In this case, the relic density is [1]

$$\Omega_X \sim \frac{\text{pb}}{\sigma(\bar{X}X \rightarrow \text{SM})}. \quad (1)$$

That is, the correct relic abundance  $\Omega_X \sim 1$  is obtained for an annihilation cross section typical for a perturbative interaction of a weak-scale particle. Such particles are called weakly interacting massive particles (WIMPs), and Eq. (1) is sometimes called the “WIMP miracle.” It suggests that dark matter may be connected with the weak scale, and hence may be observable at the LHC.

Another hint for the existence of WIMPs comes from attempts to understand particle physics at the weak scale. Particle physics models that address the stability of the weak scale against quantum corrections generally have “partners” of standard model particles with masses of order 100 GeV–1 TeV whose role is to cancel the UV sensitivity of the electroweak order parameter. The most well-studied example is that of supersymmetry (SUSY), with a SUSY partner for every standard model particle, but “little Higgs” and models with extra dimensions also fall into this class. Furthermore, these models naturally satisfy precision electroweak constraints if the partner particles cannot be singly produced, implying an approximate “partner parity” under which the partners are odd and standard model particles are even. If this

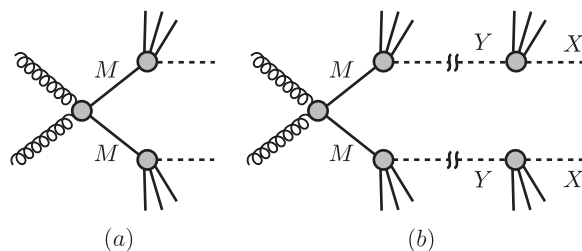


FIG. 1: Collider production of dark matter (a) in conventional WIMP dark matter models, (b) in superWIMP/ADM models.

parity symmetry is exact, the lightest odd particle is absolutely stable, and generically has the mass and interactions to be WIMP dark matter.

If this picture is correct, the prospects for obtaining experimental evidence for it are excellent. Dark matter direct and indirect detection experiments are reaching levels of sensitivity where a signal is expected. Also, the CERN Large Hadron Collider (LHC) will explore the weak scale with  $pp$  collisions with energies up to 14 TeV, leading to the exciting possibility that dark matter can be produced and studied in the laboratory. However, the connection between dark matter production at colliders and the cosmological dark matter density is very indirect. The production of WIMPs at colliders occurs via pair production of the standard model partners with the strongest couplings to protons (typically colored partners), followed by cascade decays to standard model particles and dark matter particles (see Fig. 1a). This is not directly related to the  $\bar{X}X$  annihilation process that determines the cosmological relic density, and knowledge of the underlying model is required to relate them. The program of relating collider data to cosmological dark matter is extremely ambitious, and may require colliders beyond the LHC (*e.g.* a high-energy  $e^+e^-$  collider) [2].

However, there are other models of dark matter in which there is an explanation of the dark matter as compelling as Eq. (1), and also fit well with particle physics

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at the weak scale, but where the program of relating collider and cosmological data is at first sight even more difficult, perhaps even impossible. In this Letter we show that in many cases these involve displaced vertices visible in particle detectors, and these substantially improve the prospects for connecting collider and cosmological data. We will discuss these ideas in the context of SUSY, specifically the minimal supersymmetric standard model (MSSM), but it is straightforward to extend them to other particle theory frameworks. We consider two possibilities in particular.

**SuperWIMP models** [3]: In these models, the lightest supersymmetric particle in the visible sector is the next-to-lightest SUSY partner (NLSP)  $Y$ , and decays to a SUSY particle  $X$  in the dark sector. It is assumed that  $X$  is sufficiently weakly coupled that it is never in thermal equilibrium, in which case its relic density is set by the decay of  $Y$  particles after they freeze out. We then obtain

$$\Omega_X \sim \frac{m_X}{m_Y} \frac{\text{pb}}{\sigma(\bar{Y}Y \rightarrow \text{SM})}. \quad (2)$$

This preserves the motivation of Eq. (1) as long as  $m_Y \sim m_X$ . This is natural if the masses of both  $X$  and  $Y$  arise from breaking SUSY or electroweak symmetry.

**Asymmetric dark matter (ADM) models** [4]: In these models the dark matter density arises from a relic particle-antiparticle asymmetry in the dark matter particles  $X$ . The visible sector has a baryon and lepton asymmetry in the early universe that explains the fact that the universe is composed of matter (and not anti-matter) today. These asymmetries may be related [5, 6], giving a common origin of the baryon and dark matter relic densities. In ADM models the lepton and baryon asymmetry is transferred to  $X$  via interactions that are in equilibrium in the early universe but drop out of equilibrium at a temperature  $T \gtrsim m_X$ . The  $X$  density is then related to the baryon density by

$$\frac{\Omega_X}{\Omega_B} \sim \frac{m_X}{m_B}, \quad (3)$$

where  $m_B \sim 1$  GeV is the baryon mass. This prediction only depends on the  $X$  mass, giving the correct dark matter abundance for  $m_X \sim 10$  GeV, close to the weak scale.

Remarkably, both classes of models predict displaced vertices from NLSP decays (see Fig. 1b). Dark matter therefore gives another motivation for displaced decay searches in addition to those in the literature (*e.g.* Ref. [7]). In superWIMP models the long-lived NLSP arises because  $Y$  transfers its relic abundance to  $X$  by decaying after it freezes out at a temperature  $T_Y \sim m_Y/25$ . This implies

$$\Gamma(Y \rightarrow X \cdots) \lesssim H(T_Y) \sim \frac{c}{10 \text{ m}} \left( \frac{m_Y}{100 \text{ GeV}} \right)^2. \quad (4)$$

This corresponds to a typical displaced vertex of the order of the size of an LHC detector, another interesting ex-

ample of a “cosmic coincidence.” The literature on superWIMPs has focused on decays via gravitational strength couplings with much longer decay lengths, and the possibility of decays inside the detector was not emphasized.

In ADM models, the light dark matter particle is generally the LSP and the operator that transfers the particle-antiparticle asymmetry to the dark sector allows the NLSP to decay. This decay must be out of equilibrium at temperatures  $T \sim m_X \sim 10$  GeV, otherwise the asymmetry in the dark sector is diluted. This again gives a displaced vertex of order 10 m for  $m_Y \sim 100$  GeV.

It is of course possible that  $c\tau$  of the NLSP is much longer than the detector radius  $R$ . However even in this case the NLSP will decay inside the detector with probability  $R/(\gamma\beta c\tau)$ . The parameter space for models with observable displaced vertices therefore extends to models with decay lengths much longer than 10 m (see *e.g.* Ref. [8]). We will show that the observation of even a few displaced decays substantially improves the prospects of reconstructing the events and measuring the parameters relevant for cosmology. If the NLSP is electrically charged, it can be tracked to reconstruct the event fully, and it may be trapped and its late decays studied [9, 10]. Our results are therefore of particular interest for the case of uncharged NLSPs.

## II. DISPLACED DECAY PHENOMENOLOGY

We begin by classifying the models in which the decay lengths can saturate the bound Eq. (4). In superWIMP models  $X$  must be out of equilibrium at temperatures above the  $Y$  freeze-out temperature. This happens naturally for renormalizable couplings, which decouple at high temperatures. Non-renormalizable couplings would have to be out of equilibrium at the reheat temperature, effectively the highest temperature reached by the universe, resulting in much longer minimum decay lengths. In the MSSM, the only possible renormalizable couplings to a neutral superWIMP  $X$  are the superpotential couplings

$$XH_u H_d \quad \text{and} \quad XLH_u. \quad (5)$$

For the first operator  $X$  is  $R$  parity even and the dark matter is the fermion component of  $X$ ; for the second  $X$  is  $R$  parity odd and the dark matter is the scalar component. Depending on supersymmetry breaking, it can be natural for the scalar component to be lighter than the fermion component. Assuming that the NLSP decays after its freeze out, scattering processes such as  $\tilde{H}\tilde{H} \rightarrow X\tilde{W}$  were never in equilibrium, unlike nonrenormalizable couplings which at high enough temperatures eventually equilibrate.

For ADM models, we require that the interaction that transfers the asymmetry be *in* equilibrium at sufficiently high temperatures, so this is required to be a non-renormalizable interaction. This interaction generally allows the NLSP to decay to one or more  $X$  particles,

as we will see below. The standard model part of the coupling must carry nonzero  $B - L$ . The simplest possible operators are those of dimension 5, all with  $B - L = \pm 1$ . These are superpotential terms of the form

$$XLLe^c, \quad XQLd^c, \quad Xu^cd^cd^c, \quad X^2LH_u, \quad (6)$$

and Kähler terms of the form

$$XLH_d^\dagger, \quad X^\dagger LH_d^\dagger, \quad X^\dagger LH_u. \quad (7)$$

Ref. [4] only considered interactions proportional to  $X^2$ , but this is not required by the ADM mechanism. With the exception of the last operator in Eq. (6),  $X$  is  $R$  parity odd and the dark matter is the  $X$  scalar. For the last operator in Eq. (6) there is a  $Z_4$   $R$  symmetry that guarantees stability of  $X$ , and the dark matter can be either the scalar or fermion component of  $X$ ; we consider the case where it is the scalar so that the NLSP decays directly into the dark matter. To obtain the correct dark matter density, the  $X$  mass must be  $\sim 6$  GeV for all of these operators except for the  $X^2LH_u$  model, which has an  $X$  mass of 12 GeV [4]. More generally, one can show that for a coupling of the form  $X^n\mathcal{O}$  one has  $m_X \simeq (6 \text{ GeV})n/|B - L|_{\mathcal{O}}$ . This assumes that the operator transferring the asymmetry freezes out at a temperature above  $m_X$ . If it freezes out at a lower temperature, the predicted mass will increase and the NLSP decay length will get shorter.

Because the minimum decay length for the NLSP is already close to the size of a detector, we focus on cases where the NLSP field appears in the operator that couples the sectors. Then there is no further suppression of the NLSP decay, so these are the models most likely to have observable displaced vertices. Given this, the possible observable NLSP decays resulting from either super-WIMP and ADM models is listed in Table 1. We have allowed the possibility of chargino NLSPs, which can occur in some situations [11]. We have not listed completely invisible decays, *e.g.*  $\chi^0 \rightarrow \nu X$  for the operator  $XLH_u$ . If we allow operators with dimension greater than 5, there are additional possibilities, such as  $\tilde{\nu} \rightarrow X\gamma\gamma$  from the operator  $XLH_uW^\alpha W_\alpha$ , where  $W_\alpha$  is a standard model gauge field strength superfield.

### III. RECONSTRUCTION

Reconstructing decays with displaced vertices is challenging at the LHC because the experiments are designed to detect particles coming from the interaction region. The visible decay products from a highly displaced vertex can travel in any direction through the detector, and require special techniques. These events should trigger on objects produced in the supersymmetric prompt cascade, so at least we can focus on offline reconstruction of these decays.

**Prompt reconstruction:** If the NLSP is charged or an  $R$ -hadron, measurements of ionization energy loss and

Coupling	NLSP Decay	NLSP Signal
$XH_uH_d$	$\chi^0 \rightarrow X + (h^0, Z)$ $\chi^\pm \rightarrow X + (H^\pm, W^\pm)$	vertex $\rightarrow (h^0, Z) + \mathcal{E}_T$ track $\rightarrow (H^\pm, W^\pm) + \mathcal{E}_T$
$XLH_u$ $XLH_d^\dagger$ $X^\dagger LH_u$	$\chi^\pm \rightarrow X + \ell^\pm$ $\tilde{\nu} \rightarrow X + (h^0, Z)$ $\tilde{\ell}^\pm \rightarrow X + (H^\pm, W^\pm)$	track $\rightarrow \ell^\pm + \mathcal{E}_T$ vertex $\rightarrow (h^0, Z) + \mathcal{E}_T$ track $\rightarrow (H^\pm, W^\pm) + \mathcal{E}_T$
$X^2LH_u$	$\chi^\pm \rightarrow 2X + \ell^\pm$ $\tilde{\ell}^\pm \rightarrow 2X + (H^\pm, W^\pm)$	track $\rightarrow \ell^\pm + \mathcal{E}_T$ track $\rightarrow (H^\pm, W^\pm) + \mathcal{E}_T$
$XLLe^c$	$\tilde{\ell}^\pm \rightarrow X + \ell'^\pm$ $\tilde{\nu} \rightarrow X + \ell' + \bar{\ell}$	track $\rightarrow \ell'^\pm + \mathcal{E}_T$ vertex $\rightarrow \ell' + \bar{\ell} + \mathcal{E}_T$
$XQLd^c$	$\tilde{\ell}^\pm \rightarrow X + u + \bar{d}$ $\tilde{\nu} \rightarrow X + d + \bar{d}$ $\tilde{u} \rightarrow X + \ell^+ + d$ $\tilde{d} \rightarrow X + \nu + d$	track $\rightarrow 2 \text{ jets} + \mathcal{E}_T$ vertex $\rightarrow 2 \text{ jets} + \mathcal{E}_T$ $R$ -hadron $\rightarrow \ell^\pm + \text{jet} + \mathcal{E}_T$ $R$ -hadron $\rightarrow \text{jet} + \mathcal{E}_T$
$Xu^cd^cd^c$	$\tilde{u} \rightarrow X + \bar{d} + \bar{d}'$	$R$ -hadron $\rightarrow 2 \text{ jets} + \mathcal{E}_T$

TABLE I: NLSP decays and signals for various operators coupling the dark matter to the MSSM. The couplings  $XLH_d^\dagger$  and  $X^\dagger LH_u$  are Kähler couplings, the rest are superpotential couplings. For the coupling  $X^\dagger LH_u$ , only the scalar NLSP decays can occur. Flavor indices have been suppressed and depend on the flavor structure of the operator that  $X$  couples to.

track curvature can determine their 4-momenta (see [12] for a review), in principle allowing complete reconstruction of the prompt part of the event. We therefore focus on the case of neutral NLSPs. We can gain important information about the prompt part of the event by determining the position and timing of the displaced vertex, without fully reconstructing the visible decay products of the vertex.

The position of the primary interaction vertex can be determined using conventional methods from the large number of hard visible particles expected from the cascade decays (see Fig. 1b). The position of the displaced vertex can in principle be determined in many parts of the detector. It is important to make use of the outer parts of the detector since the probability to decay in a region of the detector is essentially proportional to its radial size. In the tracker, the displaced vertex can be located using conventional tracking. In outer parts of the detector, the displaced decay would give activity without inner tracks pointing to it. There may be distinguishing geometric features, such as tracks that do not point radially, and studies would be needed to determine whether the vertex can be identified in these situations. Some work in this direction has already been done [13], motivated by “hidden valley” models [14].

Important additional information is obtained if the displaced vertex can be timed, thus determining the velocity of  $Y$ . Timing is probably more challenging and depends on the final state and detector in question. For decays involving muons, muon arrival times can determine the

time of flight of  $Y$ . This technique could also be used for other decay products if the decay occurs in the muon system. Timing in the hadronic or EM calorimeters can potentially extend the kinds of vertices that can be timed. Overcoming the experimental difficulty in timing measurement has a significant payoff in event reconstruction, as we will see below.

Since the decay lengths are typically larger than a detector size, we focus on the case where only one of the NLSPs decays inside the detector. We assume that the velocity of the NLSP that decays in the detector has been determined as discussed above. We need to determine the 4-momenta of the two  $Y$  particles to reconstruct the prompt event. We assume that the visible particles and missing  $p_T$  in the prompt event can be reconstructed separately from those of the displaced vertex. This may be possible only in favorable events where the hard visible particles and missing  $p_T$  from the prompt event do not point to activity associated with the displaced vertex. The missing  $p_T$  and the velocity of the NLSP gives 5 constraints on the 8 components of the  $Y$  4-momenta, so we still need 3 constraints for each such event. If we have  $n$  such events, we get  $2(2n - 1)$  constraints by imposing equality of the masses of the “mother” particles  $M$  (see Fig. 1b) and the NLSPs  $Y$ . For 2 such events, the prompt part of the event can be completely reconstructed (up to discrete combinatoric ambiguities). If the prompt decays involve additional intermediate particles we can get additional constraints [15] at the price of additional model-dependence.

More generally, the point is that the additional kinematic information from displaced vertices is very helpful in reconstructing the prompt part of the event. As another example, a single event with two displaced decays positioned allows full reconstruction of the prompt event.

**X reconstruction:** We now turn to the reconstruction of  $X$  properties. The coupling between  $X$  and  $Y$  is in principle measurable via  $Y$ ’s lifetime, indirectly given by the fraction of events with a decay in the detector, but this parameter is not usually important for calculating the dark matter density. On the other hand, the  $X$  mass is crucial in determining whether the  $X$  particle observed in a displaced vertex is the dark matter. This requires the reconstruction of the total 4-momentum of the visible decay products of the NLSP,  $p_{\text{vis}}$ , which may be highly nontrivial.

We first consider the case that the NLSP 4-momenta  $p_Y$  is known, either by measurement for a charged NLSP or determined by kinematic reconstruction as discussed above. For each such event, the invariant mass of  $p_{\text{inv}} = p_Y - p_{\text{vis}}$  then gives the mass of the invisible decay products. If there is only one invisible  $X$  particle produced in each decay, this will be the mass of  $X$ ; if there are  $n$   $X$  particles plus possible neutrinos, the mass distribution will have a lower endpoint at  $n m_X$ . The shape of the distribution then gives a handle on the value of  $n$ .

If the NLSP 4-momenta is unknown, the situation is more difficult. However, if its velocity can be determined

by vertexing and timing, we can determine  $m_X$  if a single  $X$  accounts for all of the missing energy. Given the NLSP velocity, it is possible to boost to its center of mass frame. In this frame, by energy-momentum conservation we have

$$m_Y = E_{\text{vis}} + \sqrt{m_X^2 + |\vec{p}_{\text{vis}}|^2} \quad (8)$$

where  $E_{\text{vis}}$ ,  $\vec{p}_{\text{vis}}$  are the energy and momentum of the visible decay products in the NLSP rest frame. Since this is an equation with two unknowns ( $m_Y$ ,  $m_X$ ), two events may be sufficient to solve it. Events involving decays to the same single visible particle give degenerate information, and we only get a single constraint. However, if there are events with more than one kind of visible particle (*e.g.* Higgs and  $Z$  production) the masses can be solved. We conclude that by combining a small number of events it is possible to solve for both the NLSP and LSP masses without relying on kinematic reconstruction of the prompt event.

## IV. CONCLUSIONS

In this Letter, we have discussed supersymmetric dark matter models where the relic abundance is not due to standard WIMP cosmology, specifically superWIMP and asymmetric dark matter models. In these models, the dark matter is produced at colliders only as a result of the decay of a NLSP with a macroscopic decay length, and there is no guarantee that the properties of the dark matter can be probed at collider experiments. However, for NLSP decay lengths not too far from the minimum value of order 10 m, a significant number of NLSP decays can occur inside the detector, giving rise to a rich set of possible displaced vertices at colliders.

We have shown that measuring the position and/or time delay of the displaced vertices is extremely useful for reconstructing the SUSY mass spectrum, while fully reconstructing the visible decay products of vertices can be used to determine the dark matter mass. For both superWIMP and asymmetric dark matter models the mass is the crucial parameter that connects cosmological observations of dark matter to collider data. Quantitative studies of several scenarios are under investigation. Of course the mass measurement techniques discussed here apply also to displaced decays to invisible particles that are not dark matter, *e.g.* light gravitinos [16] or neutrinos [17]. This strongly motivates overcoming the experimental challenges in the study of highly displaced vertices at colliders.

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